Trends in Power Performance Measurement Standards

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TRENDS IN POWER PERFORMANCE MEASUREMENT STANDARDS

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1. Introduction

It has been recognized that power performance measurements must be carried out with care and that a comprehensive uncertainty analysis of the measurement must be carried out. For larger wind turbines the distance between the wind turbine and the meteorology mast becomes quite long and the correlation between the wind speed and the power becomes smaller. For inhomogenous terrain, flow distorsion due to the topography ads to the uncertainty. Considering all relevant uncertainty factors, and specifically the terrain induced flow distorsions, it is not a straight forward task to measure a power curve in an inhomogenous terrain.

2. Use of power performance measurement standards

Three power performance measurement standards have been used in the resent years. These are the IEA recommendation, Ref. 1, the CEC recommendation, Ref. 2, and the Danish recommendation, Ref. 3. A comparison of these, Ref. 4, shows that they are quite comparable in the general technical procedure, considering the set up of the instrumentation, averaging times and requirements to the data base. They all have specific requirements that sensors are traceable calibrated, and that the performer of the measurements makes a thorough analysis of the terrain, and that traceability and analysis of the terrain is documented and reported; requirements that all too often are neglected. The reason to state these requirements is the knowledge that the uncertainties in power performance measurements can seem small but when a thorough uncertainty analysis is performed, the overall uncertainty in estimated annual energy production is surprisingly high. <u>Typically, the overall uncertainty of the measurement is 5-10% as a standard deviation</u>. And this is only due to the measurement uncertainties when care has been taken to traceability of sensors, selection of a good site and a thorough analysis of all uncertainties have been taken into account. <u>When a wind energy project is planned, this uncertainty of the measured power performance of a wind turbine, expressed as a standard deviation, should be taken into account</u>.

When a wind energy project have been realized, the manufacturer of the wind turbines is often faced with the requirements that he shall make a power performance measurement at the site. This is, though, often under circumstances that increases the uncertainties substantially. Wind turbines are erected at positions where they produce the most power, which means where the wind is concentrated. The requirements for a power performance measurement with low uncertainty is a site with homogenous flow, which can often be contradictory to a site with concentrated wind. This is why power performance measurements in mountainous terrain is a questionable task and often of limited value, taking all aspects into account. It might therefore be considered relevant to use alternative procedures in inhomogenous terrain.

3. Traceability of sensors

Traceability of sensors has been introduced, but what is actually meant by traceability? If you want to measure accurately your sensor, apart from being a good quality, should be calibrated against a more accurate source. This more accurate source should again be calibrated against a more accurate source, and so it should continue untill you calibrate against the fundamental units defined by BIPM (Bureau International de Pois et Mesure), which is the worldwide reference for measurements of units. This is often called the calibration chain, where each link adds more uncertainty to the accuracy.

There have been established national reference calibration laboratories in most countries, and these laboratories document their traceability through well-defined and documented procedures. The recent power performance recommendations require the documented traceability to be part of the documentation of a power curve measurement.

3. An anemometer calibration experiment

Consider we have an anemometer that is traceable calibrated and we want to calibrate another anemometer using this anemometer. You put them on top of a very slender mast at a height of 40m with a mutual distance of 2m and you only measure the wind speed of the two anemometers when the wind is perpendicular to a line between them. We now have a quite good setup for calibration of one anemometer against another. The second anemometer, though, is having a higher uncertainty due to the calibration chain, mentioned above. This way of calibrating one anemometer against a master anemometer of same type in the free air can be considered as an alternative to wind tunnel calibrations. For practical use, though, the calibration setup and the calibration procedure shall be thoroughly analysed for uncertainties that must be added to the uncertainty of the master anemometer.

We now put the other anemometer on a separate 40m mast 100m away from the master anemometer. What uncertainty should now be added to the calibration of the second anemometer? If the terrain 10 km around the masts is completely flat, for instance like a completely calm lake, the mean values of the calibration should be the same as when the distance between them is 2m. In reality, though, such ideal sites are not possible, and we must take varying topography, buildings, trees etc. into account. It seems not really realistic, though, that we can make a good anemometer calibration this way! But, in principle, this is what we are actually doing when we are performing a wind turbine power performance test!

Considering now the site as a test site for power performance measurements, and consider both anemometers calibrated. We now have a quite good setup for calibration of the test site. This way of making a site calibration before a power performance test is actually considered in the latest draft performance standards. The site calibration may, for instance, show a deviation of 0.2m/s at 8m/s. We now switch the second anemometer and its mast with a wind turbine with a rotor of 40m diameter and we have the setup of the power performance measurements on the wind turbine. But what does a site deviation of 0.2m/s at 8m/s mean to the measurement of the power curve. At this wind speed, where the efficiency of the wind turbine is normally the highest, the power is proportional to the third power of the wind speed which means a deviation of 8% on the efficiency! We shall therefore look out for site effects that are considerably less than 0.2m/s. This is the reason why power performance standards are setting more and more strict requirements to the terrain in which power performance measurements are made.

The further away the meteorology mast is from the wind turbine the more sensible the measurement setup is to site effects. The distance may neither be too little because the wind turbine may influence the flow at the meteorology mast. The best compromise seem to be a distance of 2.5 times the rotor diameter, which is required or recommended in the latest recommendations, Ref. 3 and 11.

5. Hill effects

The high uncertainties due to terrain effects lead to a parametric study on the influence of hills on power performance measurements, Ref. 5. The study is a systematic analysis of the speed up or speed down effects around two-dimensional and round Gaussian hills. The hills that are analysed are relatively small and the flow around them is smooth and it can be anticipated that there is no separation around them. The flow model WASP was used and the largest wind speed differences between two separated points 30m above ground level was determined. The distances between the points were described by multiples of a rotor diameter of 30m. The conclusion of the study was that two-dimensional hills with heights of the order of 10% of the tower height and with horizontal dimensions of the hills of the order of the tower height indicates speed-up effects above 4%. Round hills indicate half as high speed-up effects as two-dimensional hills.

The size of the hills was based on the requirements to the terrain in the Danish recommendation, Ref. 3, where the requirements are that variations in the terrain are less than 0.07, 0.1 or 0.2 times the diameter of the rotor to distances of 5, 10 or 20 times the rotor diameter, respectively. The analysis thus indicates that the terrain requirements in the Danish recommendation at the most unlucky circumstances might include terrain effects about 4%. The requirements in the Danish recommandation are quite strict, and terrain that can be accepted under these requirements are certainly not inhomogeneous. When going into mountainous terrain one can expect the terrain effects to increase proportionally to the terrain variations. If separation occurs in the hills, though, the terrain effects further increases.

6. Wake effects

Other wind turbines in the surrounding terrain influence the power performance measurement on the specific wind turbine under test. The wake of a neighbouring wind turbine can influence the measurement of wind speed at the meteorology mast or the power produced by the wind turbine. In either case requirements must be set to the distance from which wake effects should be taken into account. A study on this matter has been carried out by Frandsen, Ref. 6. He uses different wake models and comes to the conclusion, that the wake from a neighbouring wind turbine is significant for power performance tests. The neighbouring wind turbine should be of the order 20-40 (dependant on direction) times its rotor diameter away to secure less than 1% wind speed difference between the wind turbine and the meteorology mast.

No requirements to the distance to neighbouring wind turbines was set up in Ref. 1 and 2. The Danish recommandation requires an upwind distance of 35 times the rotor diameter of a single neighbouring and operating wind turbine. With reference to the above mentioned wake analysis this requirement might seem to be too strict, but the requirement of a certain distance to neighbouring wind turbines due to wake effects is now introduced in power performance recommandations, and it is certainly going to stay.

7. Boom and mast effects

When the anemometer is mounted on a mast it is often put on a boom on the mast at a certain level. This mounting arrangement introduces flow distorsion on the anemometer which must be taken into account in the uncertainty of the power performance measurement. The influence of the boom was investigated by Pedersen, Ref. 7. He put an anemometer on a boom in the wind tunnel and found that for an anemometer (Risø type, 60mm cup, 170mm rotor) with a distance of 6.8 times the boom diameter to a tubular boom with a diameter of 50mm, the variations in the cup anemometer reading during different inflow angles was between +2% and -4%. Increasing the distance to 11.8 times the boom diameter the variations were ±1%.

Mast effects have been investigated by Hirch et.al., Ref. 8, in wind tunnel. Their conclusion was that their anemometer, positioned 2-3 times the mast diameter away from a three legged lattice mast, measured variations of the order of ±8% of the wind speed outside the wake of the mast.

These wind tunnel investigations lead to the requirements in the Danish power performance recommendation, Ref. 3, that the anemometer shall be positioned at hub height on the top of a tube on top of the meteorology mast. Any other instruments shall be positioned at least 1.5m below the top mounted anemometer. Only in this case uncertainties from boom and mast effects can be neglected. These strong requirements have not been used in other recommendations, but in order not to introduce uncertainties from boom and mast effects they are highly recommended, as the uncertainties due to specific boom and mast effects are difficult to estimate.

8. A relative power performance measurement procedure

The measurement of the performance of a wind turbine in inhomogeneous terrain is difficult because the wind speed deviations from anemometer to wind turbine may be severe. For this kind of terrain a relative procedure may be an advantage. The relative procedure must eliminate or minimize all flow distorsion effects, and if the measurement in inhomogeneous terrain of the wind speed at a long distance from the wind turbine can be avoided, then it should. The measurement of the wind speed could then be made locally at the wind turbine, at a position where it is insensible to the terrain. Putting the anemometer locally at the wind turbine has also the advantage, that the correlation between the wind speed and the power is high, which means that the scatter of the points becomes low. The problem is then reduced to find the relation between the wind speed at the local position at the wind turbine and the free air wind speed. This problem can be resolved by measurements at a homogeneous site. Using this relative procedure, the local flow distorsion, from mounting the anemometer at the wind turbine, is eliminated through a calibration/measurement at a site where site uncertainties are low. It must be assumed, of course, that the wind turbine is the same, and that the plade pitch setting, rotor diameter and rotor rotational speed are exately the same.

The requirements to the position of the anemometer on the wind turbine should be considered seriously to make it insensible to the terrain, and the position of the anemometer shall be exately the same for all power performance measurements. The following requirements can be used as initial guidelines for further investigations.

oA nacelle mounted anemometer should be mounted in the symmetry plane of the nacelle. It should be mounted somewhere along the nacelle where the movements and vibrations are small. The distance from the center line of the blade root should be not less than 2.5 times the diameter of the blade root.

oThe vertical position of the anemometer should be so that it is free of the boundary layer around the nacelle. Skew air flow from below or from above due to a slope in the terrain should be taken into account. The anemometer should not be mounted in the wake of a blade root vortex, due to a sharp transition from a circular blade root to the profiled blade. The anemometer should be mounted vertically on top of a tube. It is recommended that the anemometer is mounted at a position above a 15° downwind inclined line which is tangent to the most upper part of the nacelle, hub or spinner as described in Fig. 1. It is also recommended that the anemometer is mounted outside a ±15° vortex wake sector behind a sharp transition from blade root to profiled blade. If the trailing edge of the blade is cut off at an angle less than 30° this last requirement can be neglected.

oA quality control of the position of the anemometer on the nacelle can be made by comparing the power curves measured in inhomogenous terrain for smaller sectors all around the horizon. If the power curves do not deviate for different sectors, the position of the anemometer can be considered as satisfactory.

The relative power performance measurement procedure have been used by the wind turbine industry for projects in inhomogenous terrain, and satisfactory results have been reported. There is still some lack of experience to include the procedure in the standards, but in the future the procedure is expected to be common for power performance measurements in inhomogeneous terrain.

9. Air density normalization

The latest three power performance measurement recommandations, Ref. 1-3, use normalization of the power of the wind turbine to a standard air density. For stall-regulated wind turbines and for pitch-regulated wind turbines at low wind speeds the normalization is applied to the power, but for pitch-regulated wind turbines at high wind speeds where the wind turbine regulates the power to maximum power, the normalization is applied to the wind speed. In Ref. 1-2 the density ratio is raised to a power of 1/3, based on Ref. 9, and in Ref. 3 it is raised to a power of 1/2, based on a linear relationship between power efficiency and the tip speed ratio. None of these are actually correct. The correct normalization should use the actual measured power efficiency as function of wind speed, but for power performance procedures it is rather complicated and not practical.

The normalization process can be derived by expressing the ratio of the normalized power to the measured power:

$$\frac{P_{norm}}{P_{meas}} = \frac{\frac{1}{2}\rho_{norm}V_{norm}^{3}C_{p}(V_{norm})}{\frac{1}{2}\rho_{meas}V_{meas}^{3}C_{p}(V_{meas})}$$

This ratio is an expression of C_p, and it will be different for different assumptions on the variation of C_P with the wind speed or the tip speed ratio. Fig. 2 shows different assumptions on the power coefficient C_P. Assuming the power coefficient is proportional to the inverse of the wind speed to a power of n (C_P=K/V^n) we get the following relationship:

$$\frac{P_{norm}}{P_{meas}} = \frac{\rho_{norm}}{\rho_{meas}}\left(\frac{V_{norm}}{V_{meas}}\right)^{3-n} \Rightarrow V_{norm} = V_{meas}\left(\frac{P_{norm}\rho_{meas}}{P_{meas}\rho_{norm}}\right)^{\frac{1}{3-n}}$$

Setting the power constant for the normalization and only varying the wind speed we get:

$$V_{norm} = V_{meas}\left(\frac{\rho_{meas}}{\rho_{norm}}\right)^{\frac{1}{3-n}}$$

The assumptions on n are explaned in the following.

<u>Constant power efficiency</u>

Assuming a constant power efficiency (C_P=K, n=0), the power is proportional to the wind speed to a power of three, and we get a one third power relationship:

$$V_{norm} = V_{meas}\left(\frac{\rho_{meas}}{\rho_{norm}}\right)^{\frac{1}{3}}$$

<u>Power efficiency proportional to tip speed ratio</u>

Assuming the power efficiency is proportional to the tip speed ratio (C_P=K/V, n=1), the power is proportional to the wind speed squared, and we get a one half power relationship:

$$V_{norm} = V_{meas}\left(\frac{\rho_{meas}}{\rho_{norm}}\right)^{\frac{1}{2}}$$

<u>Power proportional to wind speed</u>

Assuming the power is proportional to the wind speed (P=KV, C_P=K/V^2, n=2), and we get a linear relationship:

$$V_{norm} = V_{meas}\frac{\rho_{meas}}{\rho_{norm}}$$

<u>Constant power</u>

Assuming the power is constant (P=K, C_P=K/V^3, n=3), and we get an equation where the wind speeds disappear. This assumption can not be used because it is not possible to normalize the power by adjusting the wind speed.

In Fig. 3 the relationship for a measured power curve of a pitch-regulated Vestas V39, Ref. 10, between C_P and the tip speed ratio $X=V_{tip}/V$ is shown for wind speeds in the power regulation interval (10-17m/s). A power fit of the points gives the relationship $C_P=K^*X^{1.998}$, which means that the best of the above mentioned fits is n=2. This is equivalent to assuming the power proportional to the wind speed. Setting n=1 is an improvement compared to setting n=0, but it seems that it is better setting n equal to 2 and to use a linear normalization relationship.

10. Uncertainty analysis

It has been increasingly important to document the uncertainty of a power performance measurement, which is demonstrated by the requirements of the power performance requirements in Ref. 1-3. Recently, the basis to make uncertainty estimates have been improved substantially. In autumn 1993 ISO (International Standards Organization) issued a new guidance for uncertainty in measurements, Ref. 11. This guide is going to be referenced in the reviced standardization directives of ISO and IEC (International Electrotechnical Commitee) and is expected to be the basis for uncertainty estimates in future standardization work. The guide is a very helpful tool as a common reference basis. In annexes it explanes in detail the reasons why the guide is made the way it is. It is new that all expressions of uncertainty should be made by standard deviations. The often used expressions of uncertainties by high confidence levels is not recommended in the guide. The guide is being referenced in the new IEC commitee draft on power performance measurements, Ref. 12, but it is strongly recommended to be used also in other measurement procedures.

11. Latest IEC draft standard

Standards on design of and measurements on wind turbines is carried out within the standards organization IEC (International Electrotechnical Commitee) in Technical Commitee TC88. Under this commitee a working group was established in the autumn 1993 to make a draft on international power performance measurement procedures. This working group have now worked out a Commitee Draft, Ref. 12, which is being commented at the moment by the national commitees.

The Commitee Draft, in short, features the following main requirements:

o Requirements are set to maximum slope and variations of the terrain (max. slope 3°, 5° or 10° and max. variations 0.08*D, 0.15*D or 0.25*D to distances of 2*L, 4*L, or 8*L, respectively, where D is the rotor diameter and L is the distance between the wind turbine and the meteorology mast). Requirements are set to location of obstacles and neighbouring wind turbines (20*D_n to single upstream operating wind turbines, 7*D_n to single upstream stopped wind turbines). Maximum allowed measurement sector ±115° relative to met. mast (distance 2-4*D, 2.5*D recommended). Alternative to meet requirements is site calibration or three-dimensional flow modelling. Documentation required.

o Averaging time 10 minutes. Method of bins being used with 0.5m/s bins. Data normalized to sea level air density and closest 500m level (one half power law used for normalization of pitch-regulated wind turbines at high winds, n=1). Wind speed range covered by two alternative requirements. Minimum data base requirements 180 hours and 30 minutes per bin.

o Requirements to uncertainty analysis and documentation as integral part of power curve and annual energy production documentation. Reference to ISO guide, and detailed example.

o Data base for power curve shall be presented as scatter plots of 10 minute mean, standard deviation, max and min values. Power curve shall be presented in table and as a plot. Estimates of annual energy production shal be tabulated including uncertainty estimates, expressed as standard deviations.

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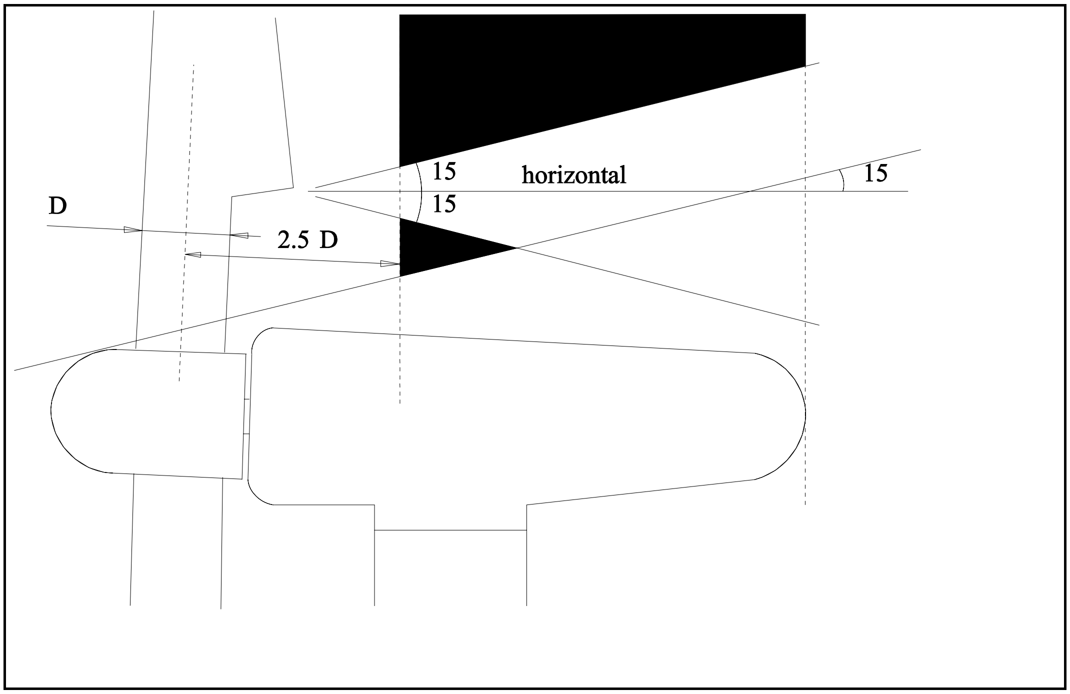

Fig. 1 Mounting of anemometer on top of nacelle. The anemometer should be mounted inside the hatched areas.

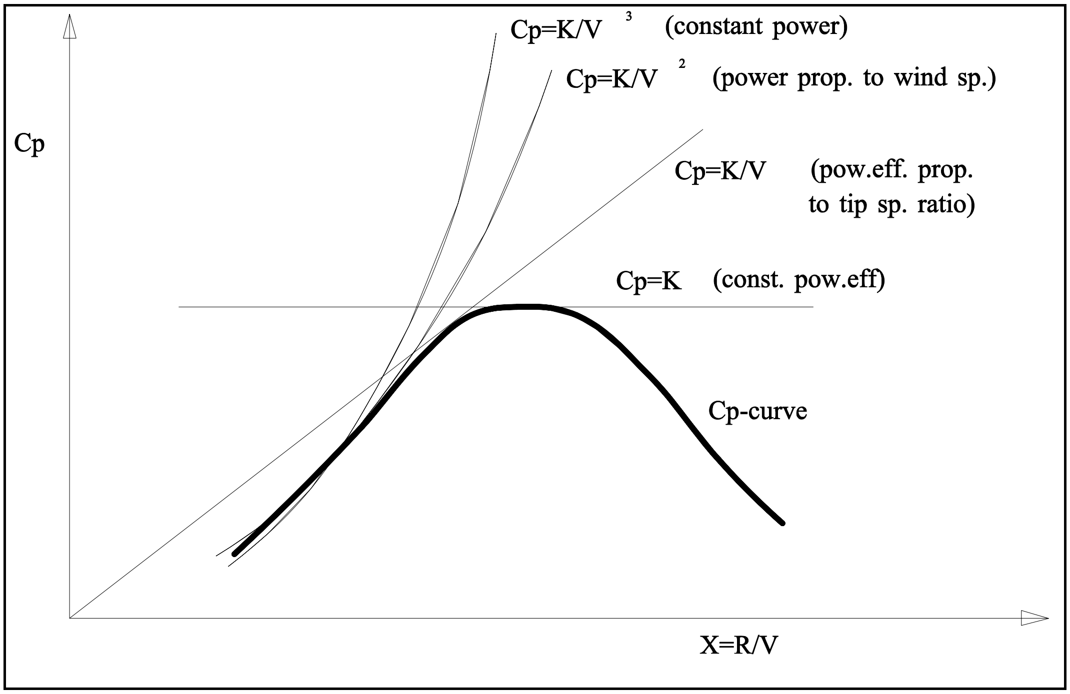

Fig. 2 Assumptions on power efficiency for pitch-regulated wind turbines at high wind speeds

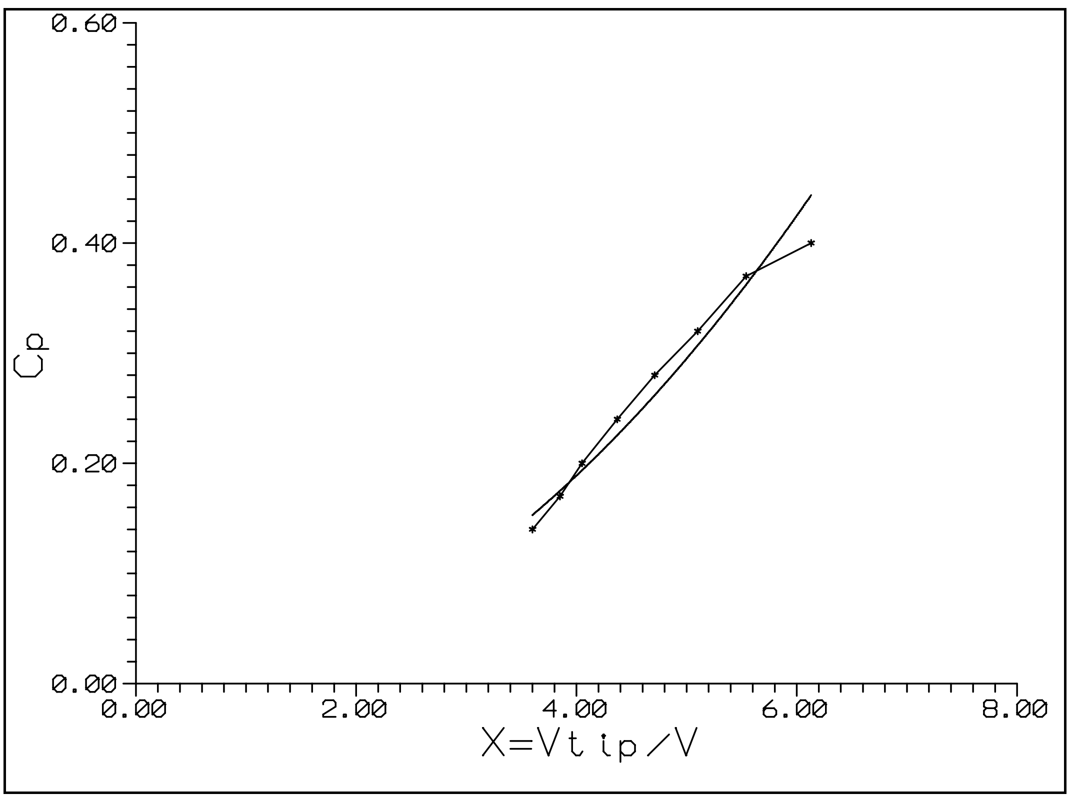

Fig. 3 C_P versus tip speed ratio $X=V_{tip}/V$ for a pitch-regulated Vestas V39 for wind speeds 10-17m/s. Best power law fit: $C_P=K^*X^{1.998}$